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# Evidence of the Cabibbo-Suppressed Decay $\Lambda_c^+ \to p\, K^- K^+$

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## Abstract

We report evidence for the Cabibbo-suppressed decay of the charm baryon $\Lambda_c^+$ into the final state $pK^-K^+$ . The analysis is performed on data collected by high energy photoproduction experiment E687 during the 1990-91 Fermilab fixed target run. The branching ratio of the decay $\Lambda_c^+ \to pK^-K^+$ relative to the non-suppressed $\Lambda_c^+ \to pK^-\pi^+$ is measured to be BR( $pK^-K^+$ / $pK^-\pi^+$ )=0.096 $\pm$ 0.029 $\pm$ 0.010. The upper limit of the decay into $p\phi$ relative to the inclusive $pK^-K^+$ decay is measured to be BR( $p\phi$ / $pK^-K^+$ )< 58 % at the 90% confidence level.

Our knowledge of the physics of charm baryons is relatively poor compared to that of the charm mesons. This is because of the smaller production cross section, shorter lifetime and, in $e^+e^-$ storage rings, the absence of a high signal to background $\Lambda_c\overline{\Lambda_c}$ resonance. In particular, while numerous Cabibbo-suppressed (CS) decays of charm mesons have been measured by several experiments, observation of the CS decays of charm baryons has never been conclusively demonstrated. Only CERN experiment NA32 [1] has reported an accumulation of a few events at the $\Lambda_c^+$ mass in $pK^-K^+$ (4 events), $p\pi^+\pi^+\pi^-\pi^-$ (3 events), and perhaps in $p\pi^+\pi^-$. This paper reports the first definite evidence of the CS decay $\Lambda_c^+ \to pK^-K^+$ and the measurement of its branching fraction relative to that of the decay mode $\Lambda_c^+ \to pK^-\pi^+$ (throughout this paper, conjugate states should be implicitly assumed).

E687 is a high energy photoproduction experiment at Fermilab, whose main goal is to study charm particle physics. Heavy quark states were produced by bremsstrahlung photons of average (tagged) energy $E_\gamma = 220$ GeV incident on a 4 cm beryllium target and the decay products were detected by a large acceptance multi-particle spectrometer, which is described in detail elsewhere [2]. A vertex detector composed of 12 planes of silicon microstrips performed high resolution tracking in the region immediately downstream of the target, thus allowing the identification and separation of the charm production and decay vertices [3]. Downstream of the microvertex detector, tracking was accomplished by five stations of multi-wire proportional chambers and two large magnets which deflected charged particles in opposite directions. Three multicell Čerenkov counters operating in threshold mode allowed identification of charged protons, kaons and pions over a wide range of momentum. The apparatus contained a hadronic calorimeter for triggering, electromagnetic calorimeters and muon detectors. During the 1990-91 Fermilab fixed target run, approximately 500 million hadronic triggers were collected, from which a sample of approximately 100,000 reconstructed charm particle decays were obtained.

The analysis of the $\Lambda_c^+ \to pK^-K^+$ decay depends especially on the particle identification and vertex reconstruction capabilities of the detector.

The E687 Čerenkov system was able to separate kaons from protons in the momentum range 16-44 GeV/c and 61-116 GeV/c. In the momentum range 44-61 GeV/c, the system only distinguished pions from kaons and protons (K/p ambiguous). The identification requirements on the $\Lambda_c^+ \to pK^-K^+$ decay prongs were chosen to minimize the combinatorial background. The proton and/or the like-sign kaon ($K^+$) were required to be unambiguosly identified, while the unlike sign kaon ($K^-$) was loosely required to be kaon-consistent.

Any three track combination satisfying the above Čerenkov conditions and the correct charge-strangeness correlation was processed by a *candidate driven vertex algorithm*, which is described in detail elsewhere [2]. First, the three track combinations were used to construct a *secondary* or *decay* vertex. Then the computed total momentum vector and vertex of the combination were used as a "seed track" to construct a *primary* or *production* vertex by intersecting it with other tracks found by the microvertex detector. Once the production and decay vertices were determined, the distance between them, $L$, and its relative error, $\sigma_L$, were computed. The ratio of these quantities, $L/\sigma_L$, the vertex separation expressed in standard deviations, constitutes the most powerful tool in extracting the charm signal from the background. The vertex algorithm also returned the confidence levels of the reconstructed secondary and primary vertices, $cls$ and $clp$, and estimators of their respective "degree of isolation", $is1$ and $is2$. The estimator $is1$ gives the confidence level that tracks from the decay vertex came from the production vertex, while the estimator $is2$ gives the confidence level that other tracks in the event were associated with the decay vertex. Imposing cuts on these quantities has proven to be very effective in further reducing the background in many E687 data analyses.

Two other analysis conditions were imposed on the $\Lambda_c^+ \to pK^-K^+$ candidates to improve the signal-to-noise ratio. First, the total momentum of the decay prongs was required to be greater than 50 GeV/c. This is because our Monte Carlo showed very low acceptance for $\Lambda_c^+$ baryons produced with momentum less than $\sim 40$ GeV/c, while the background has a large low-momentum component. Second, the proper time of the decay was required to be less than five times the nominal $\Lambda_c^+$ lifetime (as measured by our experiment in Ref. [4]). According to the Monte Carlo, this cut retained 98% of the $\Lambda_c^+$ events while rejecting 14% and 45% (respectively) of the longer-living reflections from $D_s^+$ and $D^+$ mesons due to possible Čerenkov misidentification.

Figure 1 shows the $\Lambda_c^+ \to pK^-K^+$ signals selected by two different choices of the analysis conditions described above (looser conditions in 1(a) and tighter conditions in 1(b)). The histograms were fitted with a Gaussian curve for the signal plus a straight line for the background. The masses returned from the fit are compatible with the $\Lambda_c^+$ nominal mass [5], and the widths are in good agreement with the width of $6.6 \pm 0.1$ MeV/$c^2$ predicted by our Monte Carlo simulation.

The behavior of the $\Lambda_c^+ \to pK^-K^+$ signal with each of the cuts used in the analysis was investigated and compared with Monte Carlo predictions. In particular, Figure 2 shows the $pK^-K^+$ survival yield as a function of the detachment cut $L/\sigma_L$, for both data and Monte Carlo. The excellent agreement demonstrates that the observed signal behaves with the expected $\Lambda_c^+$ lifetime.

Possible contaminations to the $pK^+K^-$ invariant mass distribution due to other charm hadron decays were also investigated. Specifically, three major sources of contamination were considered: $D^+ \to K^+K^-\pi^+$, $D_s^+ \to K^+K^-\pi^+$ and $\Lambda_c^+ \to pK^-\pi^+$ . In each of these decay modes, if one of the decay prongs is misidentified by the Čerenkov counters, the invariant mass can reflect into the region near the $\Lambda_c^+ \to pK^-K^+$ invariant mass. A quantitative estimate using our Monte Carlo showed that the contribution in the $\Lambda_c$ region coming from these decays is negligible (less than one entry).

We measured the branching ratio of $\Lambda_c^+ \to pK^-K^+$ relative to the $\Lambda_c^+ \to pK^-\pi^+$ decay. Figure 3 shows the $pK^-\pi^+$ signal used in the measurement. The same analysis conditions (except for the Čerenkov requirements) as for the $pK^-K^+$ signal were applied, in order to reduce any possible systematic effect. The histogram was fitted with a Gaussian curve for the signal plus a second degree polynomial for the background, giving a yield of $775.7 \pm 66.0$ events. To calculate the branching ratio, we used the $\Lambda_c^+ \to pK^-K^+$ signal in Figure 1(a), refitting it with width fixed to the Monte Carlo value, so that the yield is $30.3 \pm 8.7$ events. The reconstruction efficiencies were computed by generating one million events in each decay channel and averaging over the whole momentum distribution (which is well represented by the Monte Carlo): they are $(0.83 \pm 0.01) \times 10^{-2}$ for the $\Lambda_c^+ \to pK^-K^+$ mode, and $(2.03 \pm 0.01) \times 10^{-2}$ for the $\Lambda_c^+ \to pK^-\pi^+$ mode (the difference between the two efficiencies is due mainly to the different Čerenkov conditions). The branching ratio is then computed to be:

$$BR\,\frac{(\Lambda_c^+ \to pK^-K^+)}{(\Lambda_c^+ \to pK^-\pi^+)} = 0.096 \pm 0.029.$$

This number includes a correction which takes into account the fact that the two decays produce different final state hadrons, which have different absorption probability in the production target and microvertex detector. Since the $\pi^+$ from $\Lambda_c^+ \to pK^-\pi^+$ is absorbed more frequently than the $K^+$ from $\Lambda_c^+ \to pK^-K^+$ , this correction lowers the branching ratio by about 1.8%.

Extensive systematic studies and consistency checks were performed on the branching ratio measurement. These studies included the variation of the analysis cuts one at a time, the use of different sets of analysis conditions, the variation of the Monte Carlo parameters (mass and lifetime of the generated $\Lambda_c^+$), the use of momentum-dependent efficiency curves instead of global reconstruction efficiencies, and the separation of the two run periods (1990 and 1991). The branching ratio was always found to be consistent within the statistical fluctuations.

Although the systematic effects appear to be small compared to the statistical errors, an upper limit on the systematic error can be computed. This was obtained by summing in quadrature the error on the Monte Carlo efficiencies, a contribution due to uncertainties in the Monte Carlo simulation of our Čerenkov detectors, and a contribution which estimated possible uncertainties in the fits of the two signals. The last contribution was computed by using different fit techniques, different parametrizations of the background, and by fixing the width of the Gaussian fits to the signal or letting it vary freely, and was found to be the dominant contribution to the systematic error (being 0.008). The total systematic error was computed to be 0.010. The final result for the branching ratio is:

$$BR\,\frac{(\Lambda_c^+ \to pK^-K^+)}{(\Lambda_c^+ \to pK^-\pi^+)} = 0.096 \pm 0.029\,(stat) \pm 0.010\,(syst).$$

For completeness, we investigated the size of the resonant contribution $\Lambda_c^+ \to p\phi$ , even though the signal is statistically weak. NA32 results [1], based on only 4 events, suggest that this resonant mode could be the dominant part of the $pK^-K^+$ decay. Figure 4 shows the $pK^-K^+$ mass distribution for the same analysis cuts used in Figure 1(a) with the additional requirement that the $K^+K^-$ invariant mass be within $\pm 3\sigma$ of the nominal $\phi$ mass. The mass distribution was fitted with a line plus a Gaussian whose width was fixed to the Monte Carlo value, giving the yield $6.1 \pm 2.8$ events. On the other hand, requiring the $K^+K^-$ mass to be contained within a $\phi$ sideband (properly normalized), yielded a number of $\Lambda_c$ events of $2.0 \pm 1.8$. The number of resonant events is therefore $4.1 \pm 3.4$. Since the evidence for the $p\phi$ signal is weak, we prefer to only quote an upper limit on the branching ratio of the resonant component to the inclusive $\Lambda_c^+ \to pK^-K^+$ decay:

$$BR\,\frac{(\Lambda_c^+ \to p\phi)}{(\Lambda_c^+ \to pK^+K^-)} < 0.58$$

at the 90% confidence level.

In conclusion, we have presented evidence for the Cabibbo-suppressed decay $\Lambda_c^+ \to pK^-K^+$ . The branching ratio with respect to the $\Lambda_c^+ \to pK^-\pi^+$ mode is measured to be BR( $pK^-K^+$ /$pK^-\pi^+$ )=$0.096 \pm 0.029 \pm 0.010$. We have also observed a possible resonant component $p\phi$ to the $\Lambda_c^+ \to pK^-K^+$ decay. The upper limit on the branching ratio is measured to be BR( $p\phi$ /$pK^-K^+$ ) $< 0.58$ at the 90% confidence level.

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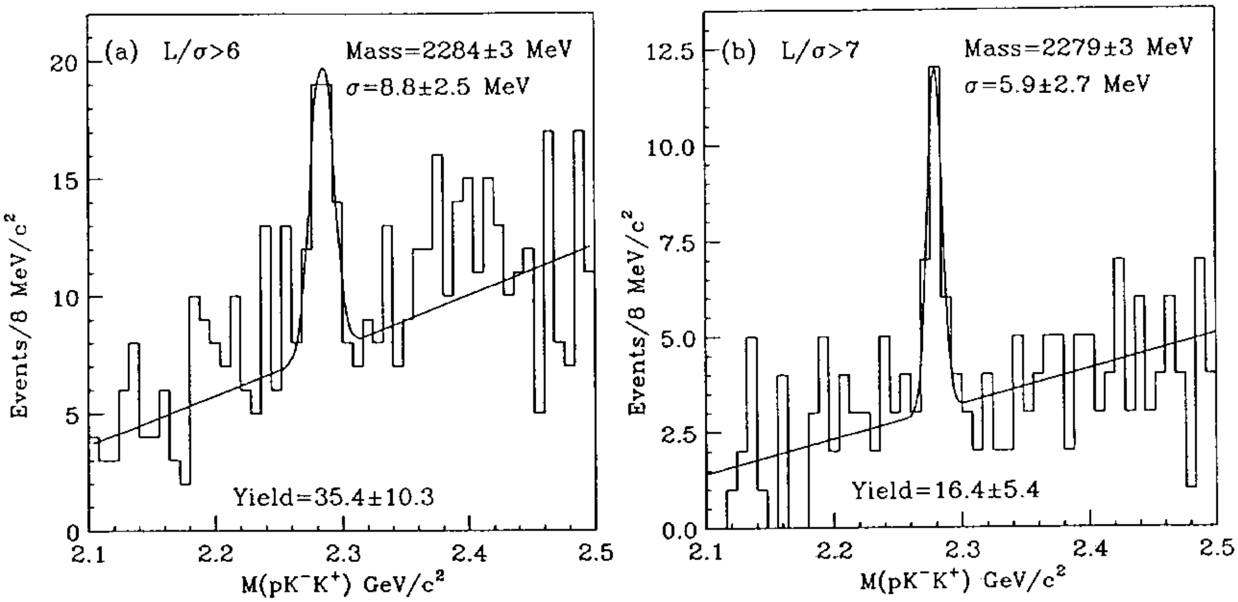


FIG. 1. $pK^-K^+$ invariant mass distribution selected with the following cuts: 1(a) $cls > 1\%$, $clp > 1\%$, $is1 < 90\%$, $is2 < 1\%$, $L/\sigma_L > 6$ ; 1(b) $cls > 5\%$, $clp > 1\%$, $is1 < 90\%$, $is2 < 0.01\%$, $L/\sigma_L > 7$

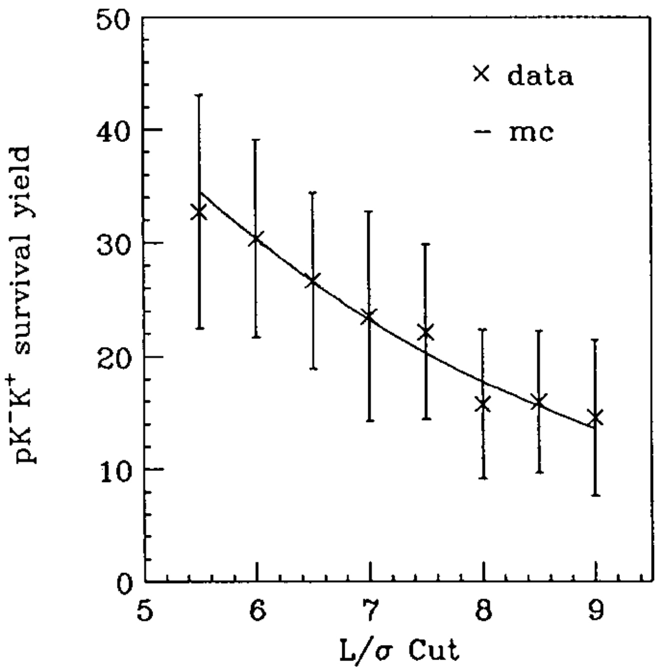


FIG. 2. Comparison between data and Monte Carlo for the $\Lambda_c^+ \to pK^-K^+$ signal as a function of the detachment cut $L/\sigma_L$. The data yields were determined by fitting the signals with width fixed to the Monte Carlo prediction. The two set of points were normalized at $L/\sigma_L > 6$. The solid line joins the Monte Carlo points.

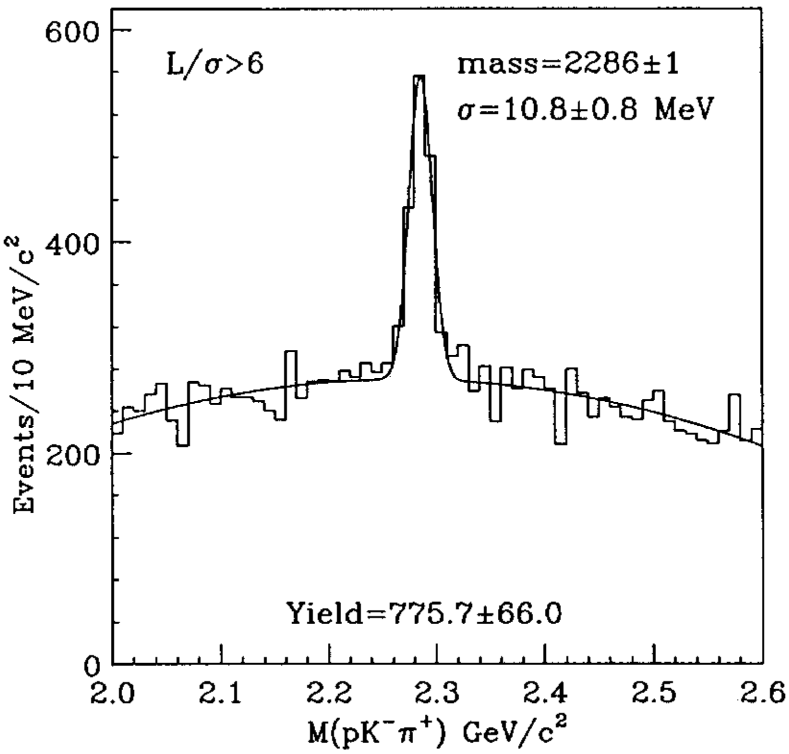


FIG. 3. $\Lambda_c^+ \rightarrow pK^-\pi^+$ signal used for the branching ratio calculation. The same analysis conditions as for Figure 1(a) are applied, except for the Čerenkov requirements.

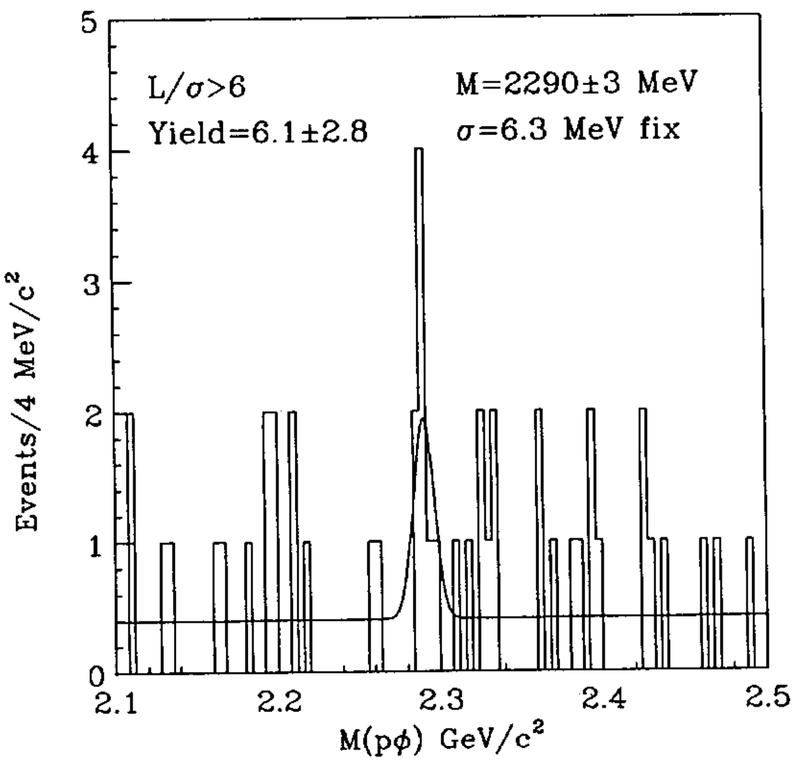


FIG. 4. $pK^-K^+$ invariant mass distribution for the same cuts as in Figure 1(a) and the additional requirement: $1.008 < m(K^+K^-) < 1.032$ GeV.